Research Article

Risk Identification and Assessment during the Excavation of the Deep Foundation Pit

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This study presents a new model for identifying and evaluating high-risk factors in foundation pit excavation. The model combines the fuzzy decision-making trial and the evaluation laboratory (FDEMATEL), the entropy weight method, and the multiattributive border approximation area comparison (MABAC) method. Firstly, the risk factors such as geology, surrounding environment, monitoring, construction, and management are studied in detail. Secondly, the subjective weight is calculated by the fuzzy DEMATEL method, and the objective weight is calculated by the entropy weight method. Then, the MABAC method is introduced to identify the key risk factors of the foundation pit and the risk level of foundation pit construction. Finally, Jinan Rail Transit R2 Line Kaiyuan Road Station is used as a case study for analysis based on the risk assessment model. The results show that the model can identify key risk factors in different construction stages of foundation pits, which can provide guidance for risk management decision-making.

1. Introduction

China's urban rail transit is developing rapidly and many cities are under construction of urban rail transit projects. By the end of 2020, China had opened a total of 7978.19 km of urban rail transit lines, of which the length of the newly added line is 1241.99 km [1]. Subway deep foundation pit project is a key link in the construction of urban rail transit. Due to the complex construction environment and the large excavation depth, it has become the main source of risk in the process of subway construction. During the construction of the foundation pit, project accidents often occur, which has become a major safety hazard [2, 3]. In order to reduce the risk of accidents during the construction of station foundation pit project, it is necessary to develop a new model

to be suitable for actual project, identify high-risk factors at each construction stage, and provide guidance for the safety of foundation pit project.

At present, many scholars have conducted certain research on the safety evaluation of deep foundation pit construction and have developed many evaluation methods based on probability analysis such as the fault tree method [4], the risk matrix method [5], and the Monte Carlo method [6]. Although each method has its own characteristics, which greatly promotes the development of risk management, these methods require complete and accurate data, and the uncertainty in the construction process of foundation pit project is large, which is difficult to meet its requirements, resulting in certain defects in practical application. To solve these problems, some scholars introduce the fuzzy set theory

into risk assessment. Wei et al. [7] determined the weights based on fuzzy analytic hierarchy process (AHP) and used evidence theory to evaluate the risk of foundation pit. Lin et al. [8] combined the fuzzy set theory with machine learning method to realize dynamic risk assessment of foundation pit and improved the accuracy of assessment results. Wang and Chen [9] combined the fuzzy comprehensive evaluation method and the Bayesian network to evaluate the risk of foundation pit project from three aspects of risk probability, loss, and controllability. Meng et al. [10] used analytic hierarchy process and fuzzy set theory to evaluate the risk of foundation pit supporting. Deng et al. [11] used the fuzzy analytic hierarchy process to determine the risk level of subway deep foundation pit construction and put forward the corresponding risk control measures. The introduction of fuzzy set theory expands the application of evaluation methods in uncertain environment, but it is also very important to reasonably calculate the weight of indicators. The above research does not consider the correlation between indicators when calculating the weight. There is a mutual correlation among indicators in foundation pit engineering, so their correlation needs to be considered. The DEMATEL method can calculate their weights by considering the causal relationship between indexes [12]. Xu et al. [13] used the FDEMATEL method to determine the key factors of slow development of China's hydrogenation station construction. Qi et al. [14] used the improved DEMATEL method to analyze the causal relationship in the evaluation system of mining construction and determine the key factors of mining construction. Although the DEMATEL method considers the influence relationship between indicators, it relies on the experience of decision makers and has strong subjectivity. It is necessary to introduce objective weighting methods to reduce its subjectivity. The entropy weight method is an objective weight determination method, which can make full use of the information of actual data and has been widely used in underground engineering [15, 16]. Combining the subjective and objective weight method, the weight is more reasonable.

There are many risk factors in the process of deep foundation pit construction. How to identify the highest risk factors is a multicriteria decision-making problem. The multiattributive border approximation area comparison method (MABAC) is a multiattribute decision-making method, ranking alternatives and considering potential losses and benefits [17]. Many scholars combine it with other decision methods to make multicriteria decisions. Luo and Liang [18] introduced language neutral number to improve MABAC method and proposed an evaluation model of roadway support optimization scheme. Liang et al. [19] combined fuzzy set theory and MABAC method to effectively evaluate the rock burst grade of tunnel surrounding rock under fuzzy environment. Wang et al. [20] proposed a q-rung orthopair fuzzy MABAC model to solve the safety evaluation of construction projects. Shahiri Tabarestani and Afzalimehr [21] identified flood-prone areas based on MABAC theory and weight of evidence. Therefore, the MABAC method can be introduced into a foundation pit project to identify the most critical risk factors in foundation pit project construction system.

In this study, fuzzy set theory and DEMATEL method are used to calculate the subjective weight, which not only considers the correlation between indicators, but also considers the uncertainty in the construction process. The entropy weight method is used to determine the objective weights. The objective weights and subjective weights are combined into combination weighting, which can use the objective data in the construction process to reduce the subjectivity of evaluation. Finally, the MABAC method is introduced to determine the key risk factors and risk level of each construction stage, and an actual project is taken as a case to verify the feasibility of the model.

2. Methods

Foundation pit construction is a complicated project. In different construction stages, there are different geological conditions, the deformation of the enclosure structure and other risk information. Therefore, the different construction phases need to be evaluated. This model can evaluate it based on the risk information of each construction stage. Considering the fuzziness and complexity of decision-making environment, this model uses fuzzy set theory, DEMATEL theory, and entropy weight method to expand the application of MABAC theory in uncertain environment. The combined weighting method not only considers the relationship between indicators, but also makes full use of the objective monitoring data in the construction process, making the weight of each indicator more reasonable. The evaluation model is shown in Figure 1. The main steps are as follows:

(1) Collect real-time data of the current construction stage and make appropriate preprocessing.

(2) Collect and analyze similar project information, determine potential risk factors, and establish a risk evaluation index system.

(3) Analyze the causal relationship between the factors and use the fuzzy DEMATEL method to determine the subjective weight of each factor.

(4) Determine the evaluation criteria, invite experts to evaluate each index, and use the entropy weight method to determine the objective weight.

(5) Identify high-risk factors and risk level at the current stage through the MABAC method.

(6) Take control measures for high-risk factors. If the high-risk factors are within an acceptable range, continue construction; otherwise, stop construction.

2.1. Fuzzy Decision-Making Trial and the Evaluation Laboratory. The decision-making trial and the evaluation laboratory (DEMATEL) is a method to solve complex and comprehensive decision-making problems, which can describe the interdependence between factors [22]. The FDEMATEL method is the combination of the DEMATEL method and the fuzzy set theory, which is the application of
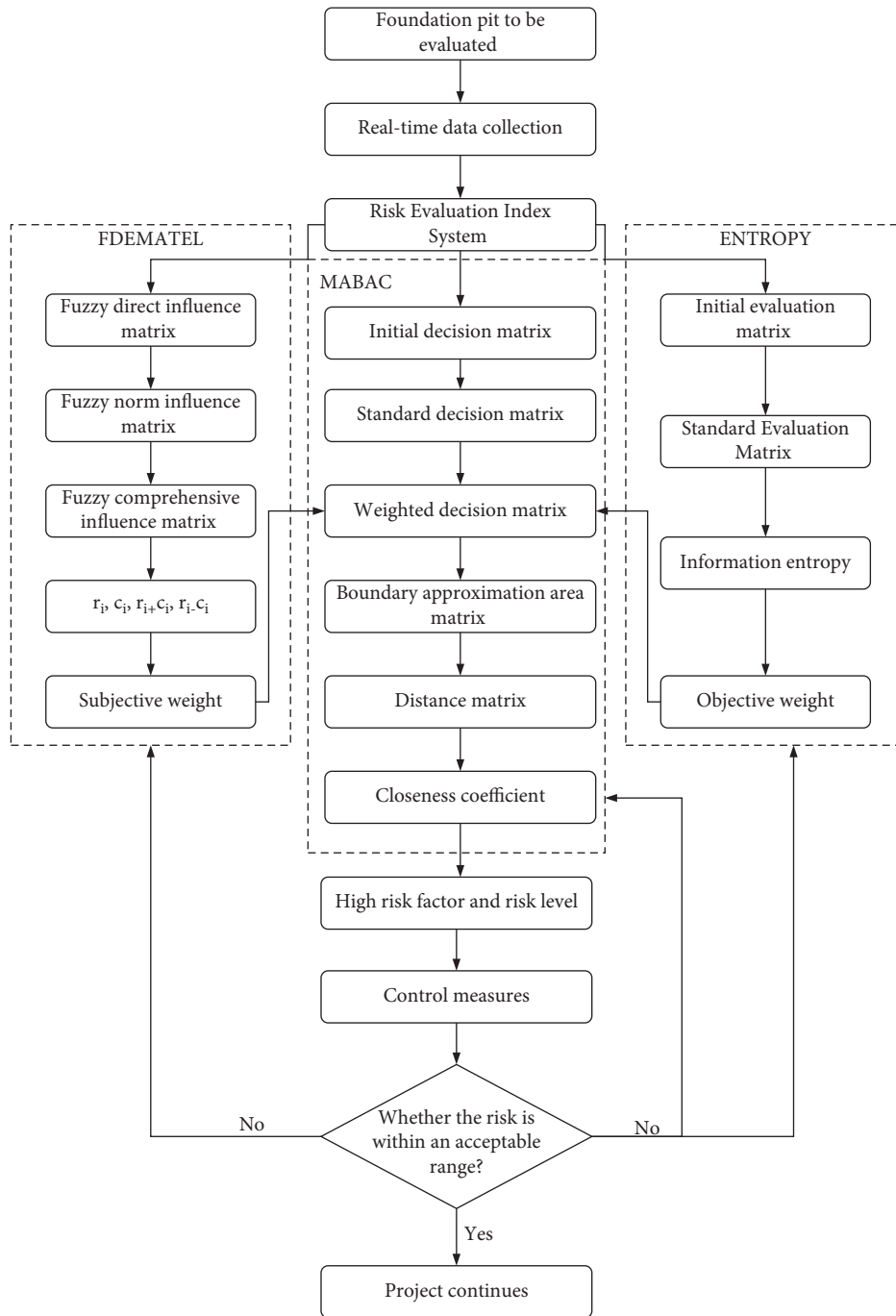
FIGURE 1: Assessment flowchart.

DEMATEL method in uncertain systems [23]. The specific steps are as follows:

Step 1: compare the degree of influence between each element to form a fuzzy direct influence matrix **E**. This study uses triangular fuzzy numbers to describe the evaluation language. Evaluation criteria are shown in Table 1.

$$e_{ij} = \left(l_{ij}, m_{ij}, u_{ij} \right),$$ (1)

$$\mathbf{E} = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ e_{n1} & e_{n2} & \cdots & e_{nn} \end{bmatrix},$$ (2)

where e_{ij} is a triangular fuzzy number, which indicates the degree of influence of the ith index on the jth index. m is the largest possible value, and l and u are the upper and lower limits of the smallest possible value.

Step 2: establish the fuzzy norm influence matrix **F** on the basis of the fuzzy direct influence matrix.

$$\alpha = \max\left(\sum_{j=1}^{n} u_{ij} \right),$$

$$\mathbf{F} = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{n1} & f_{n2} & \cdots & f_{nn} \end{bmatrix},$$ (3)

$$f_{ij} = \frac{e_{ij}}{\alpha}.$$

Step 3: solve the fuzzy comprehensive influence matrix **T**.

$$\mathbf{T} = \lim_{w \to \infty} \left(\mathbf{F} + \mathbf{F}^2 + \cdots + \mathbf{F}^w \right),$$

$$\mathbf{T} = \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1n} \\ t_{21} & t_{22} & \cdots & t_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_{n1} & t_{n2} & \cdots & t_{nn} \end{bmatrix},$$ (4)

Where $t_{ij} = \left(l_{ij}'', m_{ij}'', u_{ij}'' \right),$

Matrix $\left[l_{ij}'' \right] = \mathbf{F}_l \times \left(1 - \mathbf{F}_l \right)^{-1},$

Matrix $\left[m_{ij}'' \right] = \mathbf{F}_m \times \left(1 - \mathbf{F}_m \right)^{-1},$

Matrix $\left[u_{ij}'' \right] = \mathbf{F}_u \times \left(1 - \mathbf{F}_u \right)^{-1}.$

Step 4: defuzzification:

The fuzzy comprehensive influence matrix is defuzzified based on (5) to get the matrix **O**:

$$o_{ij} = \frac{l_{ij} + 4m_{ij} + u_{ij}}{6},$$ (5)

$$\mathbf{O} = \begin{bmatrix} o_{11} & o_{12} & \cdots & o_{1n} \\ o_{21} & o_{22} & \cdots & o_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ o_{n1} & o_{n2} & \cdots & o_{nn} \end{bmatrix}.$$ (6)

Step 5: calculate the influence degree r_i and affected degree c_i of each index. The sum of influence degree and affected degree is the center degree. The higher the value is, the more important the index is. The difference between the influence degree and the affected degree is the cause degree. If the value is greater than zero, it means that the factor affects other factors. If the value is less than zero, it means that the factor is affected by other factors.

$$r_i = \sum_{j=1}^{n} o_{ij} \quad (i = 1, 2, \ldots, n),$$ (7)

$$c_i = \sum_{i=1}^{n} o_{ij} \quad (j = 1, 2, \ldots, n).$$ (8)

Step 6: calculate the weight value.

After getting the influence degree and the affected degree, the relation matrix **D** is obtained from equation (9), and its diagonal element is defined as the influence degree vector **D**. The weight w_i is obtained by equation (10).

$$\mathbf{D} = r_i^T c_i,$$ (9)

$$w_i = \frac{d_i}{\sum_{i=1}^{n} d_i}.$$ (10)

2.2. Entropy Weight Method. In order to reduce the influence of human subjective factors, the entropy weight method is used for weighting. The entropy weight method is an objective weighting method, which determines the weight according to the amount of information contained in the index. The more the index information, the greater the variability, the smaller the entropy value, and the greater the weight; otherwise, the smaller the weight [24, 25]. The main calculation steps are as follows:

Step 1: construct the initial evaluation matrix **A**.

Assuming there are m evaluation objects and n evaluation indicators, an evaluation matrix **A** is constructed based on the original data.

$$\mathbf{A} = \left(a_{ij} \right)_{mn} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix},$$ (11)

where a_{ij} is the jth evaluation index of the ith evaluation object, $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$.

TABLE 1: Influence degree and triangular fuzzy number.

Influence degree	Triangular fuzzy numbers
No influence	(0, 0, 0.25)
Low influence	(0, 0.25, 0.5)
General influence	(0.25, 0.5, 0.75)
High influence	(0.5, 0.75, 1)
Very high influence	(0.75, 1, 1)

Step 2: due to the difference in the unit and value of each indicator, the evaluation matrix needs to be standardized. The standardized equation is as follows:

$$\text{positive index: } b_{ij} = \frac{a_{ij} - \min a_{ij}}{\max a_{ij} - \min a_{ij}},$$

$$\text{negative index: } b_{ij} = \frac{\max a_{ij} - a_{ij}}{\max a_{ij} - \min a_{ij}}, \quad (12)$$

where a_{ij} is the initial data, $\max(a_{ij})$ is the maximum value of a_{ij}, and $\min(a_{ij})$ is the minimum value of a_{ij}.

Step 3: calculate the information entropy of each index.

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} c_{ij} \ln c_{ij}, \quad (13)$$

where $c_{ij} = b_{ij} / \sum_{i=1}^{m} b_{ij}$.

Step 4: calculate the weight of each index.

$$w_j = \frac{u_j}{\sum_{j=1}^{n} u_j}, \quad (14)$$

where $u_j = 1 - e_j$, $\sum_{j=1}^{n} w_j = 1$.

The combination weight is calculated as follows:

$$w_k = \alpha w_i + (1 - \alpha) w_j, \quad (15)$$

where α is the combination coefficient, which is 0.5 in this study.

2.3. Multiattributive Border Approximation Area Comparison.

The multiattributive border approximation area comparison method (MABAC) was proposed by Pamucar and Cirovic in 2015. Because of its simple calculation process and stable solution, it is a reliable decision-making tool. Its core is to determine the best solution by calculating the distance between the alternative and the approximate region of the boundary. The results of relevant research prove that the method is more stable than other multicriteria decision methods, such as TOPSIS, COPRAS, and VIKOR, , and it is a reliable method for decision-making [26, 27]. The principles and steps are as follows:

Step 1: construct the initial decision matrix.

Suppose there are m alternatives $\mathbf{A}_i$ ($i = 1, 2, \ldots, m$) and n evaluation indicators C_j ($j = 1, 2, \ldots, n$), x represents the jth evaluation index value of the ith alternative, and the initial decision matrix $\mathbf{X}$ can be expressed as

$$\mathbf{X} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}. \quad (16)$$

Step 2: standardize the elements of the initial evaluation matrix $\mathbf{X}$; the standardization rules are the same as the entropy method.

$$N = \begin{bmatrix} n_{11} & n_{12} & \cdots & n_{1n} \\ n_{21} & n_{22} & \cdots & n_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ n_{m1} & n_{m2} & \cdots & n_{mn} \end{bmatrix}. \quad (17)$$

Step 3: calculate the weighting matrix $\mathbf{Z}$. The element z_{ij} in the matrix is calculated according to the following equations:

$$\mathbf{Z}_{ij} = w_k \times (n_{ij} + 1),$$

$$\mathbf{Z} = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1} & z_{m2} & \cdots & z_{mn} \end{bmatrix}$$

$$= \begin{bmatrix} w_1 \cdot (n_{11} + 1) & w_2 \cdot (n_{12} + 1) & \cdots & w_n \cdot (n_{1n} + 1) \\ w_1 \cdot (n_{21} + 1) & w_2 \cdot (n_{22} + 1) & \cdots & w_n \cdot (n_{2n} + 1) \\ \vdots & \vdots & \ddots & \vdots \\ w_1 \cdot (n_{m1} + 1) & w_2 \cdot (n_{m2} + 1) & \cdots & w_n \cdot (n_{mn} + 1) \end{bmatrix}, \quad (18)$$

where m is the number of alternatives, n is the number of evaluation indexes, and w_k is the combination weight.

Step 4: calculate the boundary approximation area matrix $\mathbf{G}$.

$$\mathbf{G} = [g_1, g_2, \ldots, g_n], \quad (19)$$

$$g_i = \left(\prod_{j=1}^{m} z_{ij} \right)^{1/m}, \quad (20)$$

where z_{ij} is the basic element of the weighting matrix $\mathbf{Z}$ and m is the number of alternatives.

Step 5: after determining the boundary approximation area matrix $\mathbf{G}$, calculate the distance matrix $\mathbf{d}$ between it and the alternatives. The basic element $\mathbf{d}_{ij}$ in the distance matrix $\mathbf{d}$ is composed of the difference between the basic element z_{ij} of the weighting matrix $\mathbf{Z}$ and the basic element g_j of the boundary approximation area matrix $\mathbf{G}$.

$$\mathbf{d} = \begin{bmatrix} \mathbf{d}_{11} & \mathbf{d}_{12} & \cdots & \mathbf{d}_{1n} \\ \mathbf{d}_{21} & \mathbf{d}_{22} & \cdots & \mathbf{d}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{d}_{m1} & \mathbf{d}_{m2} & \cdots & \mathbf{d}_{mn} \end{bmatrix}$$

$$= \begin{bmatrix} z_{11} - g_1 & z_{12} - g_2 & \cdots & z_{n1} - g_n \\ z_{21} - g_1 & z_{22} - g_2 & \cdots & z_{n2} - g_n \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1} - g_1 & z_{m2} - g_2 & \cdots & z_{mn} - g_n \end{bmatrix}. \tag{21}$$

Step 6: the upper and lower boundaries approach the area.

If $q_{ij} > 0$, the alternative $\mathbf{A}_i$ belongs to the upper boundary approximation area, and if $q_{ij} < 0$, the alternative $\mathbf{A}_i$ belongs to the lower boundary approximation area. When alternative $\mathbf{A}_i$ is an ideal solution, then it should have most of the alternatives approaching the upper boundary area.

$$\mathbf{A}_i \in \begin{cases} G^+, & \mathbf{d}_{ij} > 0, \\ G, & \mathbf{d}_{ij} = 0, \\ G^-, & \mathbf{d}_{ij} < 0. \end{cases} \tag{22}$$

Step 7: solve the closeness coefficient and rank the alternatives.

$$S_i = \sum_{j=1}^{m} \mathbf{d}_{ij} \quad (i = 1, 2, \ldots, n), \tag{23}$$

where S_i is the close coefficient, the greater the value, the more close the alternative to the ideal scheme.

Step 8: calculate foundation pit risk level.

$$P = \sum_{i=1}^{n} S_i * w_k \quad (i = 1, 2, \ldots, n, \ k = 1, 2, \ldots, n), \tag{24}$$

where P is the probability of the risk occurring.

Code for risk management of underground works in urban rail transit divides engineering risks into five levels, as shown in Table 2.

3. Case Study

3.1. Project Overview. The total length of the Kaiyuan Road Station of Jinan Rail Transit R2 Line is 210.6 m, the standard section width is 18.3 m, and the average excavation depth is 16.84 m. The station is constructed by the open-cut method, and the enclosure structure is drilled grouting pile and internal support. The profile is shown in Figure 2. There are overhead power lines around, and the plan view is shown in Figure 3. There are special rocks and soil such as plain fill, residual soil, and weathered rock on the site, which are not stable enough. The underground water of the station is quaternary loose pore water and magmatic rock fissure water, which is confined water. Figure 4 is the layout of the

foundation pit monitoring. The main monitoring indexes include the horizontal displacement of the pile, the ground settlement, the vertical displacement of the pile top, the horizontal displacement of the pile top, and the supporting axial force. The foundation pit was excavated in three layers and the third stage excavation was used as a case study for analysis.

3.2. Risk Index System. The first step of safety evaluation is to determine the risk index system. On the basis of consulting the engineering literature of the same type and the description of the project staff, this study divides the risk factors into the following categories:

Geological factor: the stratum distribution of Kaiyuan Station is shown in Figure 2. There are a total of 6 types of soil layers, including plain fill, residual soil, weathered rock, and other special rocks and soils, and the soil is not stable enough. In addition, the site contains pore water and magma fissure water, which is pressure bearing, and there is a risk of water inrush during the excavation process. Therefore, the groundwater level U11 and the stratum type U12 are selected as risk factors.

Surrounding environment: limited by the construction site, mechanical operations, accumulation of project materials, and nearby buildings during the construction process will all have a certain impact on the stability of the foundation pit. Therefore, the surrounding live load U21, surrounding heap load U22, and overhead power U23 are selected as risk factors.

Foundation pit monitoring: the monitoring data can reflect the stability of foundation pit in real time and determine whether the project can continue. Therefore, the Pile horizontal displacement U31, the surface settlement U32, the vertical displacement of pile top U33, the horizontal displacement of pile top U34, and the support axial force U35 are selected as risk factors.

Construction factors: construction under complex geological conditions strictly tests the technical level of the construction personnel. Any irregular construction behavior may lead to risks. Therefore, the pile strength U41, nontimely support U42, poor dewatering effect U43, poor drainage effect U44, and overexcavation and underexcavation U45 are selected as risk factors.

Management factors: limited by other conditions, reasonable construction management can effectively reduce the probability of risk occurrence. Therefore, the management level U51 and management system U52 are selected as risk factors.

The data of the above factors can be obtained in different ways. Some come from foundation pit monitoring, such as U31, U32, U33, U34, and U35. Some come from geological survey reports, such as U11, U12, and U23. Some require experts to judge according to the actual construction situation, such as U21, U22, U41, U42, U43, U44, U45, U51, and U52. The risk index system is shown in Figure 5.

TABLE 2: Criteria for risk levels.

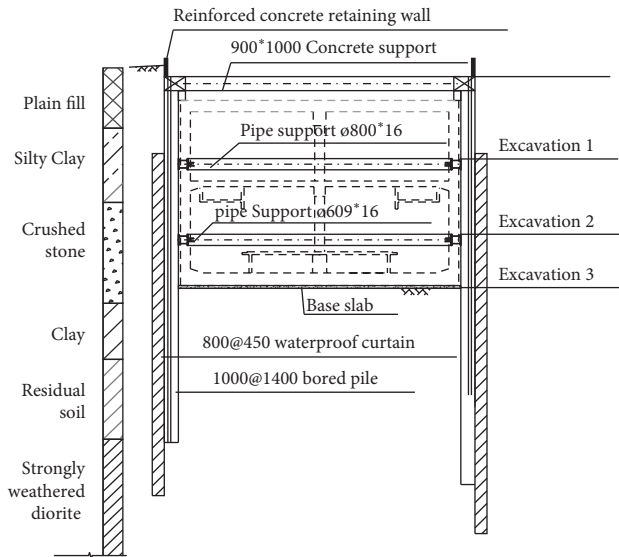| Level	1	2	3	4	5
Possibility	Frequent	Possible	Unmeant	Infrequent	Impossible
Probability	>0.1	0.01~0.1	0.001~0.01	0.0001~0.001	<0.0001

FIGURE 2: Foundation pit profile.

3.3. Subjective Weight. Considering the causal relationship between indexes, the fuzzy DEMATEL method is used to calculate subjective weights. The fuzzy direct relation matrix is established according to the rules in Table 1. Through the process of fuzzy DEMATEL, the direct relation matrix is transformed into the fuzzy comprehensive relation matrix. Then, (5)–(8) are used to defuzzify the fuzzy comprehensive relation matrix, and the influence degree, affected degree, centrality, and cause degree of the index are calculated, as shown in Tables 3 and 4.

As shown in Figure 6, the line with the degree of cause equal to 0 was used as the dividing line, the cause degree greater than 0 belongs to the cause group, and the cause degree less than 0 belongs to the influence group. Figure 6 shows that U11, U12, U21, U22, U42, U43, U44, U45, and U52 belong to the cause group and U23, U31, U32, U33, U34, U35, U41, and U44 belong to the affected group. U32, U31, and U34 are of high importance in the whole risk index system. The subjective weight of each index can be obtained by (10), as shown in Figure 7

3.4. Objective Weight. After using the fuzzy DEMATEL method to obtain the subjective weight, we need to calculate the objective weight of each index and synthesize the results of the two weights. The data of some risk factors in the risk index system can be obtained directly through measuring instruments. Others require expert judgment based on available information. Therefore, the index factors are divided into five levels as shown in Table 5 and then experts are invited to quantify according to the principle of percentile system [28]. The higher the risk level, the lower the score.

The factors that can be measured to obtain data are graded based on measurement records and similar project experience, and other factors are graded based on expert experience judgments.

Five experts are invited to this evaluation. Due to their different work experience and education, their subjective judgment will have different confidence. In order to ensure the rationality of the evaluation results, the expert confidence index (ECI) is introduced. The higher the confidence, the more reliable the expert's judgment. The index is determined by two parameters of expert's judgment ability α_m and subjective reliability β_m, and the multiplication of them is the expert's confidence θ_m. The confidence of the five experts is shown in Table 6 [29].

Multiply the expert confidence θ_m and the initial evaluation results of each indicator to form the initial decision matrix as shown in Table 7. After the relevant calculation in Section 2.2, the objective weight value of each indicator is finally obtained, as shown in Figure 8. The combination weight of each indicator is shown in Figure 9.

3.5. Identification of High-Risk Factors. After obtaining the combined weight of each indicator, the MABAC method is used to identify the most critical risk factors. The initial decision-making results of the experts in Section 3.4 are used as the initial decision-making matrix. Then use (12) to normalize it to obtain a normalized matrix, and combine the combined weights to obtain a weighted matrix as shown in Table 8.

Equations (19) and (20) are used to calculate the boundary approximation area matrix as shown in Table 9.

The distance matrix was obtained by using (21), and then the proximity coefficient of each alternative was obtained according to (23), as shown in Figure 10. It can be seen from Figure 10 that the importance of each risk factor in the third stage is ranked as U32, U43, U31, U34, U33, U12, U42, U11, U22, U21, U23, U45, U52, U35, U41, U51, and U44. According to (24) and Table 2, the *P* value is 0.075, and the risk level of foundation pit construction is level 2.

4. Discussion

It can be seen from Figure 6 that the two management factors U51 and U52 are the largest in the cause group, indicating that it has a great influence on other factors, especially in construction. Because management and construction have a direct impact, strict management can reduce substandard construction behaviors during the construction process, thereby preventing the occurrence of risk accidents. The surface settlement (U32) has the largest centrality value and a small influence value, indicating that it is the most important of all index factors and is greatly

FIGURE 3: Station plan.

affected by other factors. Because the surface settlement will lead to the settlement of nearby buildings, especially the foundation pits of subway stations, which are built in cities, nearby buildings are complex and require extremely high deformation control. At the same time, there are many factors that cause surface settlement, such as pile deformation, large surrounding loads, poor dewatering effect, and overexcavation and underexcavation. Therefore, when determining the weights of indicators, the relationship between them must be considered.

As shown in Figure 9, comparing the weight values of various factors, it can be seen that the two weighting methods assign them different weight values. The fuzzy DEMATEL method assigns the greatest weight to the surface settlement (U32), and it is considered that it has the most complicated relationship in the index system, so it assigns the greatest weight. According to the actual data, the entropy weight method assigns the maximum weight to the poor dewatering effect (U43). The fuzzy DEMATEL method is a subjective weight calculation method. Although the interrelationship between indicators is considered, expert opinions play a leading role in the evaluation process and are too subjective. The entropy weight method is an objective weight calculation method, which makes full use of the objective data in the construction process, but the data itself may have some errors. In some special project background, it needs to rely on expert experience to make decisions. It is impossible to guarantee the safety of the project completely relying on the data. The combined weight value is between the subjective weight value and the objective weight value, which effectively solves the problems caused by being completely subjective and completely objective. Therefore, the combination of subjective and objective weight method is the most reasonable.

As shown in Figure 10, the MABAC method identified surface settlement as the most critical risk factor in the third phase of the foundation pit construction, and the poor dewatering effect and the horizontal displacement are also critical. As the excavation depth of the foundation pit increases, the factors resulting in ground subsidence have also

increased. The excavation unloading of soil will cause surface settlement, and the dewatering of suspended waterproof curtain foundation pit is also an important factor that cannot be ignored. In addition, the mechanical construction and material accumulation around the foundation pit will affect the surface settlement. In order to prevent the occurrence of water inrush accidents in the foundation pit, the dewatering of the foundation pit is an important factor. The underground water in the station is abundant and pressure-bearing, and there are many types of stratum and uneven distribution, which brings difficulties to the foundation pit dewatering work. In addition, the poor dewatering effect caused by the failure to closely combine the survey report and specifications in the construction process is also an important reason. The displacement of the pile body is synchronized with the surface settlement, so limiting the displacement of the pile body in the project can achieve the effect of reducing the surface settlement.

In the third stage of excavation, due to the excessive horizontal displacement rate of piles and surface settlement, the monitoring system issued several warnings. A water inrush event occurred during the construction of this foundation pit, as shown in Figure 11. The reason is that the dewatering effect of foundation pit is poor, and the predetermined water level is not reached, which leads to the groundwater gushing in the process of excavation. The evaluation results are consistent with the actual situation, which proves the rationality of the method.

In order to control the surface settlement, the following control measures can be taken. For the settlement caused by precipitation, the precipitation rate can be changed and the depth of each precipitation can be reduced. The suspension waterproof curtain foundation pit is equipped with a recharge well outside the foundation pit to control the underground water level. For the surface settlement caused by excavation unloading, layered and block excavation method is adopted and the excavation depth is appropriately reduced. Support is carried out in time to reduce the deformation of envelop enclosure. Pouring the bottom plate as soon as possible can also reduce the settlement of the
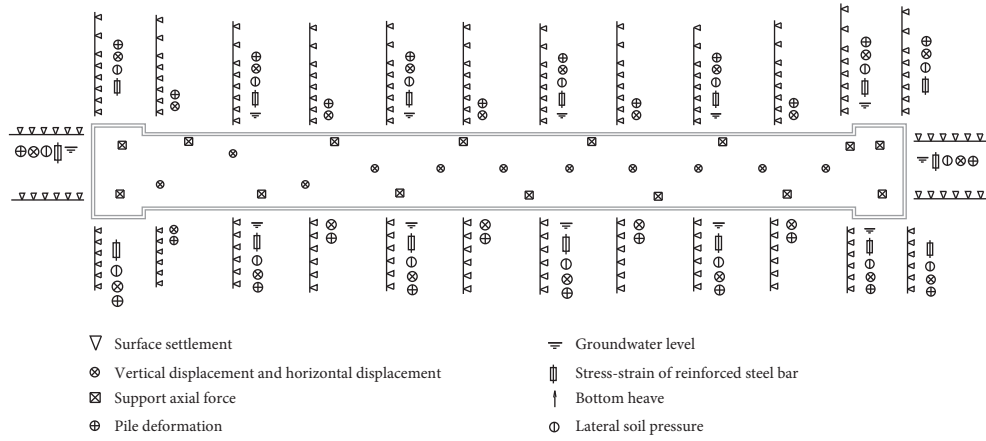
- ▽ Surface settlement
- ⊗ Vertical displacement and horizontal displacement
- ⊠ Support axial force
- ⊕ Pile deformation
- ꞊ Groundwater level
- ▯ Stress-strain of reinforced steel bar
- ꞏ Bottom heave
- ⓪ Lateral soil pressure

FIGURE 4: Monitoring points.
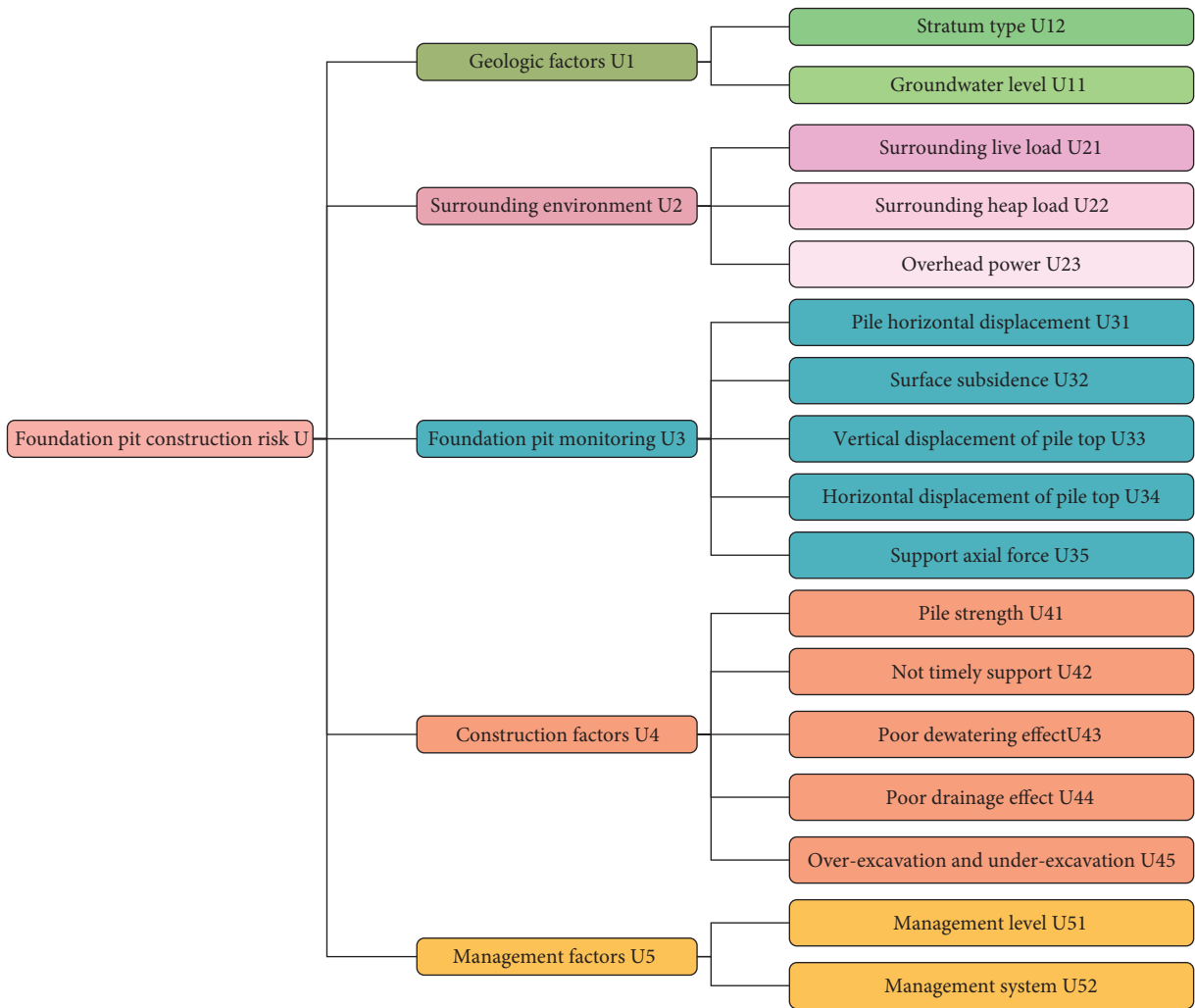
FIGURE 5: Risk assessment index system.

TABLE 3: Comprehensive relation matrix.

Indexes	U11	U12	U21	...	U45	U51	U52
U11	0.032	0.028	0.028	...	0.032	0.029	0.028
U12	0.037	0.032	0.032	...	0.036	0.033	0.032
U21	0.035	0.030	0.030	...	0.034	0.031	0.030
...	...	...	...	...	...	...	...
U45	0.033	0.028	0.028	...	0.032	0.029	0.028
U51	0.045	0.032	0.032	...	0.098	0.033	0.032
U52	0.046	0.033	0.033	...	0.101	0.062	0.033

TABLE 4: Centrality and causality.

Indexes	U11	U12	U21	...	U45	U51	U52
r_i	0.916	1.148	1.047	...	0.925	1.172	1.237
c_i	0.686	0.476	0.476	...	0.665	0.520	0.476
$r_i + c_i$	1.602	1.624	1.524	...	1.589	1.691	1.713
$r_i - c_i$	0.230	0.672	0.571	...	0.260	0.652	0.761
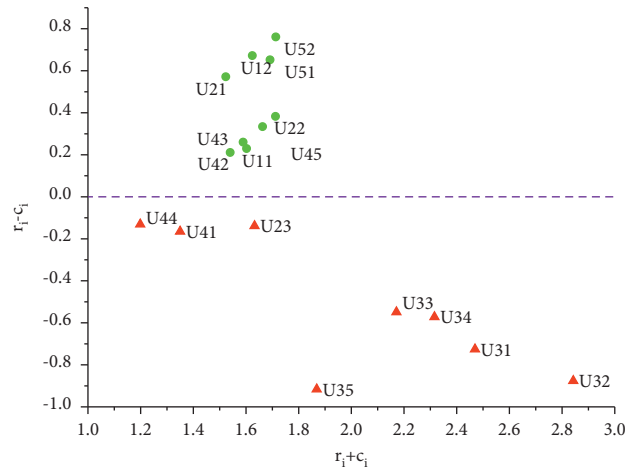
FIGURE 6: Causal relationship.
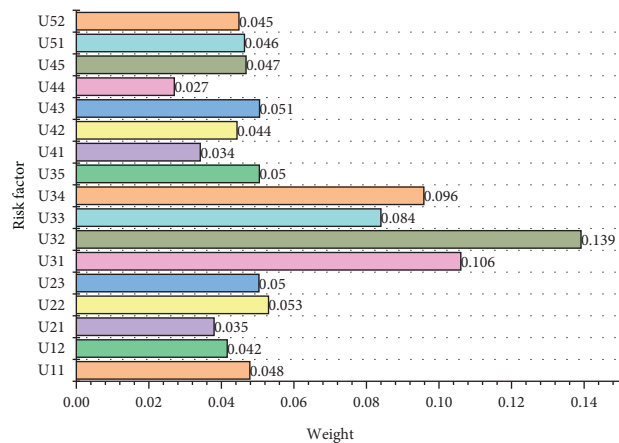
FIGURE 7: Subjective weight.

TABLE 5: Risk level.

Risk factors	Risk level				
	I	II	III	IV	V
Groundwater level (m)	16–20	12–16	7–12	3–7	0–3
Stratum type	80–100	60–80	40–60	20–40	0–20
Surrounding live load	80–100	60–80	40–60	20–40	0–20
Surrounding heap load	80–100	60–80	40–60	20–40	0–20
Overhead power	80–100	60–80	40–60	20–40	0–20
Pile horizontal displacement (mm)	0–6	6–12	12–18	18–24	24–36
Surface settlement (mm)	0–8	8–16	16–24	24–32	32–40
Vertical displacement of pile top (mm)	0–2.5	2.5–5	5–7.5	7.5–10	10–12.5
Horizontal displacement of pile top (mm)	0–3	3–6	6–9	9–12	12–15
Support axial force (kN)	0–800	800–1600	1600–2400	2400–3200	3200–4000
Pile strength	80–100	60–80	40–60	20–40	0–20
Nontimely support	80–100	60–80	40–60	20–40	0–20
Poor dewatering effect	80–100	60–80	40–60	20–40	0–20
Poor drainage effect	80–100	60–80	40–60	20–40	0–20
Overexcavation and underexcavation	80–100	60–80	40–60	20–40	0–20
Management level	80–100	60–80	40–60	20–40	0–20
Management system	80–100	60–80	40–60	20–40	0–20

TABLE 6: Expert confidence.

	Education	Work experience (years)	Judgment ability α_m	Subjective reliability β_m	Confidence θ_m
E1	PhD student	18	1	0.9	0.9
E2	Postgraduate	15	1	0.8	0.8
E3	Postgraduate	12	0.8	0.9	0.72
E4	PhD student	16	0.9	0.9	0.81
E5	Postgraduate	13	0.8	1	0.8

TABLE 7: Initial decision matrix.

	U11	U12	U21	...	U45	U51	U52
E1	61.2	56.7	67.5	...	61.2	67.5	72
E2	52.8	52	60	...	52	62.4	64
E3	46.8	44.64	51.84	...	47.52	57.6	56.16
E4	52.65	55.08	56.7	...	52.65	60.75	63.18
E5	51.2	48	56	...	52	60.8	60
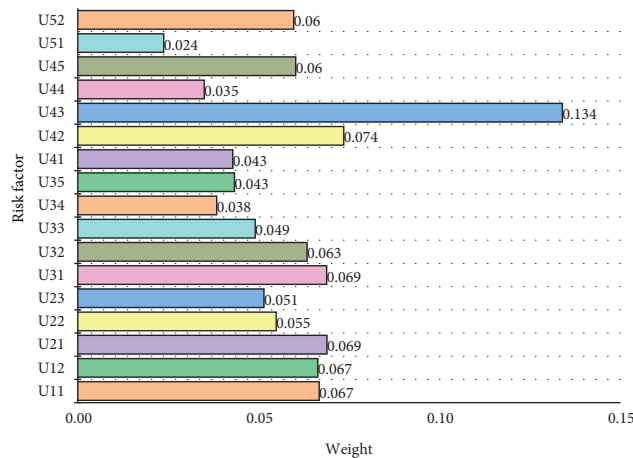
FIGURE 8: Objective weight.
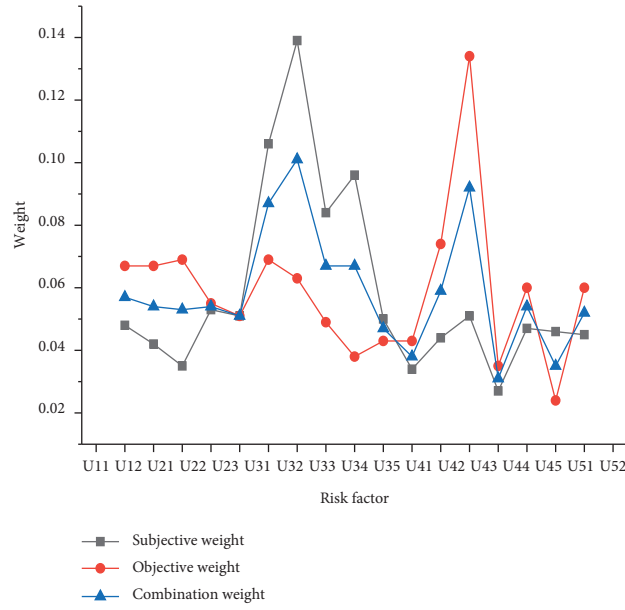
FIGURE 9: Combination weight.

TABLE 8: Weighting matrix.

	E1	E2	E3	E4	E5
U11	0.115	0.081	0.057	0.081	0.075
U12	0.108	0.087	0.054	0.101	0.069
U21	0.108	0.084	0.054	0.078	0.078
U22	0.102	0.081	0.051	0.075	0.069
U23	0.175	0.143	0.087	0.139	0.126
U31	0.101	0.196	0.136	0.203	0.155
U32	0.133	0.101	0.067	0.110	0.086
U33	0.095	0.119	0.067	0.123	0.134
U34	0.094	0.056	0.047	0.065	0.066
U35	0.077	0.048	0.038	0.057	0.055
U41	0.118	0.084	0.059	0.083	0.066
U42	0.184	0.133	0.092	0.136	0.149
U43	0.062	0.049	0.031	0.051	0.045
U44	0.107	0.071	0.054	0.074	0.071
U45	0.070	0.052	0.035	0.046	0.046
U51	0.105	0.078	0.052	0.075	0.065
U52	0.105	0.084	0.057	0.085	0.078

TABLE 9: Boundary approximation area matrix.

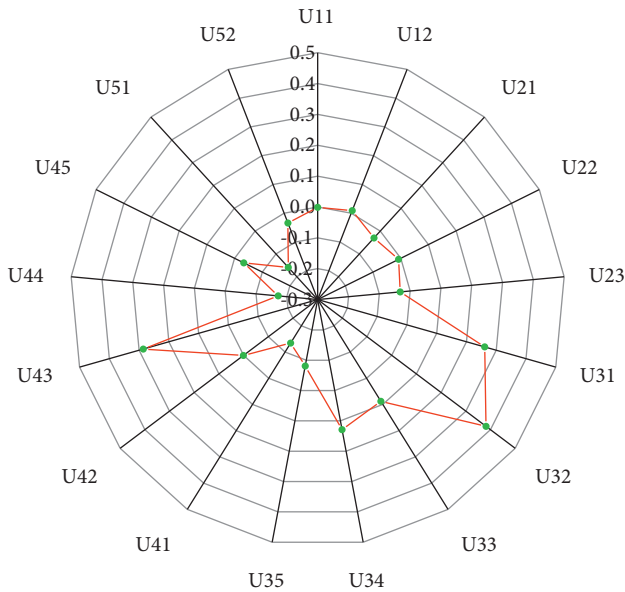|	E1	E2	E3	E4	E5
g_i	0.105	0.084	0.057	0.085	0.078

Figure 10: Closeness coefficient.

Figure 11: Water flush.

ground. During the construction of the foundation pit, the surrounding area of the foundation pit shall not be overloaded. After taking control measures, judge whether the risk is within an acceptable range and whether the construction can continue according to the monitoring data of surface settlement.

5. Conclusions

This research proposes a foundation pit construction risk assessment model based on fuzzy DEMATEL-entropy-MABAC theory and proposes corresponding risk control measures. The Jinan Rail Transit R2 Line Kaiyuan Road Station is used as a case study to analyze and verify the feasibility of the model.

(1) This model combines the fuzzy set, the DEMATEL method, the entropy weight method, and the MABAC method to identify high-risk factors in each construction stage of a foundation pit. The fuzzy DEMATEL method determines subjective weights, the entropy weight method determines objective weights, and the MABAC method ranks potential

risk factors. Confidence indicators are introduced to improve the reliability of evaluation results.

(2) There are complex causal relationships among the factors in the risk index system of foundation pit project. The fuzzy DEMATEL theory can not only consider the causal relationship between indicators but also adapt to the uncertainty in the process of foundation pit construction. The entropy weight method can reduce the influence of subjectivity on the evaluation results. The weight obtained by combining the two methods is more scientific and reasonable.

(3) The MABAC theory calculates the closeness coefficient of each index, identifies the most critical risk factors in the construction process of foundation pit engineering, determines the risk level of foundation pit, and ranks the importance of each factor. The results provide guidance for the risk management of construction and management personnel and make targeted measures.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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